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A new gravitational lens from the MUSCLES survey: ULAS J082016.1+081216

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ABSTRACT

We present observations of a new double-image gravitational lens system, ULAS J082016.1+081216, of image separation 2.3 arcsec and high (∼6) flux ratio. The system is selected from the Sloan Digital Sky Survey (SDSS) spectroscopic quasar list using new high-quality images from the UKIRT (United Kingdom Infrared Telescope) Deep Sky Survey (UKIDSS). The lensed quasar has a source redshift of 2.024, and we identify the lens galaxy as a faint red object of redshift 0.803 ± 0.001. Three other objects from the UKIDSS survey, selected in the same way, were found not to be lens systems. Together with the earlier lens found using this method, the SDSS–UKIDSS lenses have the potential to significantly increase the number of quasar lenses found in SDSS, to extend the survey to higher flux ratios and lower separations, and to give greater completeness which is important for statistical purposes.

Key words: gravitational lensing – galaxies: quasars: general – galaxies: quasars: individual: ULAS J082016.1+081216.

1 INTRODUCTION

More than 100 cases of strong gravitational lensing are now known in which quasars are multiply lensed by foreground galaxies, about the same quantity as the number of galaxy–galaxy lensing systems. The two types of system have different advantages. Systems with lensed galaxies are usually extended and therefore typically provide more constraints on the first derivative of the gravitational potential, as has been shown by the large survey of such systems from the Sloan Digital Sky Survey (SDSS), Sloan Lens Advanced Camera for Surveys (SLACS; Bolton et al. 2006, 2008; Koopmans et al. 2006). On the other hand, time delay measurements of variations in the images of lensed quasars provide a measurement of the combination of the Hubble constant H_0 (Refsdal 1964) and the average surface density of the lens in the annulus between the images used to determine the delay (Kochanek 2002). Moreover, the selection effects are often different; galaxy–galaxy systems such as the SLACS survey are usually selected based on the lenses, whereas lensed quasars are usually selected based on the sources. This has important implications for statistical studies.

In many cases, the statistics of a well-selected set of gravitational lenses can provide important cosmological information. The original application of source-selected lens samples, the determination of combinations of the cosmic matter density $\Omega_{\rm m}$ and cosmological constant density Ω_Λ in units of the critical density (Fukugita et al. 1992; Maoz & Rix 1993; Kochanek 1996) has now been largely superseded by other methods such as studies of the cosmic microwave background, supernova brightness and baryon acoustic oscillations. However, once the global cosmological model is known, the statistics of gravitational lensing can provide important information about the evolution of galaxies. Early studies used the radio sample Cosmic Lens All-Sky Survey (CLASS; Browne et al. 2003; Myers et al. 2003) which contained 13 quasar lenses in a statistically complete sample (22 lenses overall) of radio sources with 5-GHz flux density $\geq$30 mJy. One major use of such samples is the 'lens–redshift' test (Kochanek 1992) in which knowledge of the lens and source redshifts and image separations can be used to make inferences about galaxy evolution, given a global cosmology. This was used by Ofek, Rix & Maoz (2003) and most recently by Matsumoto & Futamase (2008) to derive limits on the evolution of the galaxy number density and velocity dispersion, in terms of the redshift evolution of a fiducial number density and velocity dispersion from a Schechter-like function. In surveys to date, the available sample of lenses is consistent with no evolution up to $z \sim 1$ and a standard Λ cold dark matter (ΛCDM) cosmology, but expansion of the sample is desirable in order to enable a more stringent test. Capelo & Natarajan (2007) study the robustness of this test, concluding that larger and more uniform samples of lenses, with complete redshift information and good coverage of separation distributions, are required.

In recent years, larger samples have become available by investigation of quasars from the Sloan Digital Sky Survey quasar list (Schneider et al. 2007). These have been used by Inada and collaborators (e.g. Inada et al. 2003a, 2008) to discover 30 lensed quasars to date, which form the SDSS Quasar Lens Search (SQLS;

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Table 1. Details of the Keck-I observations, showing the objects (with names representing J2000 coordinates), the SDSS redshift and r magnitude, image separations (measured from the UKIDSS images) and the exposure times in the blue and red arms. All observations were carried out on the night of 2009 February 17 using the LRIS spectrograph.

Object	z_{SDSS}	r_{SDSS}	Exp. (blue) (s)	Exp. (red) (s)	Separation (arcsec)
J033248.5−002155	1.713	18.36	1800	1650	1.1
J034025.5−000820	0.619	20.13	1600	1560	1.4
J082016.1+081216	2.024	18.97	1450	1400	1.9
J091750.5+290137	1.816	18.07	1540	1400	1.0

Oguri et al. 2006). Optical surveys are somewhat more difficult to carry out, in that the high resolution needed to separate the components of the lens system is less easily available in the optical; the CLASS survey, which had a limiting lens separation of 0.3 arcsec, showed that the median lens separation is of the order 0.8 arcsec.

Although the SDSS covers a large fraction of the sky to a relatively faint ($r \sim 22$) limiting magnitude, with the Legacy DR7 spectroscopy now totalling 9380 deg^2, the point spread function (PSF) width of the images is typically 1.4 arcsec. More recently the UKIRT (United Kingdom Infrared Telescope) Deep Sky Survey (UKIDSS; Lawrence et al. 2007) has become available; the UKIDSS Large Area Survey (ULAS) now covers just over 1000 deg^2 to a depth of $K = 18.4$ (corresponding to $R \sim 24$ for a typical elliptical galaxy at $z = 0.3$) and, importantly, has a median seeing of 0.8 arcsec. UKIDSS uses the UKIRT Wide Field Camera (WFCAM; Casali et al. 2007); the photometric system is described in Hewett et al. (2006), and the calibration is described in Hodgkin et al. (2009). The pipeline processing and science archive are described in Irwin et al. (in preparation) and Hambly et al. (2008).

We are therefore conducting a programme (Major UKIDSS–SDSS Cosmic Lens Survey, or MUSCLES) which aims to discover lenses difficult for or inaccessible to the SQLS due to small separation, high flux ratio or a combination of the two. We have used data from the UKIDSS fourth data release in this work. In an earlier paper, we reported the discovery of the first lens found in this way (ULAS J234311.9−005034; Jackson, Ofek & Oguri 2008). Here we describe a second detection of a lens system, of relatively large separation but with a relatively faint secondary. In Section 2 we describe the survey selection and observations. In Section 3 we discuss the results, including the three objects rejected as lenses and the evidence that ULAS J082016.1+081216 is a lens system. Finally, in Section 4 we revisit the survey selection in the light of the two lenses discovered by the MUSCLES programme, to assess its potential to discover new lenses which are of smaller separation and/or higher flux ratio.

2 SAMPLE SELECTION AND OBSERVATIONS

Objects were selected from the Fourth Data Release (DR4) of UKIDSS, and compared against the SDSS quasar catalogue (SDSS DR5; Schneider et al. 2007). Of the 77 429 SDSS quasars, 6708 objects were identified, due mainly to the limited area coverage of current UKIDSS. These were then inspected by eye for extensions, although we are currently developing algorithms for supplementing with objective selection from parameters fitted to the UKIDSS images. We identified 150 good candidates, of which 14 had already been ruled out by other observations (mainly SQLS), and seven (not including ULAS J234311.9−005034; Jackson et al. 2008) were known lenses. The survey rediscovered all known lenses in the current UKIDSS footprint.[1] Of the 129 remaining objects, one, ULAS J234311.9−005034, was observed previously by us and found to be a lens (Jackson et al. 2008). In this work we describe observations of four further objects from the candidate list.

These four objects were observed using the Keck-I telescope on Mauna Kea on the night of 2009 February 17, using the LRIS-ADC (low resolution imaging spectrograph–atmospheric dispersion corrector) double-beam imaging spectrograph (Oke et al. 1995). They were selected as the most convenient objects for observation at the available time, which appeared on subjective examination to be the most likely lenses, and which had estimated sizes which could be resolved by the seeing of the observations, roughly 1 arcsec. The blue arm of the spectrograph was used with a central wavelength of 430 nm, and the red arm with a central wavelength of 760 nm. A dichroic cutting between 560 and 570 nm was used to split the light between the two arms. A long slit of width 0.7 arcsec was used, with a position angle chosen so as to cover the extended structure seen in the UKIDSS images. A list of objects observed together with integration times is given in Table 1, and UKIDSS images of the observed objects are presented in Fig. 1.

Data were reduced by bias removal, using the overscan strip at the edge of each chip, followed by extraction and flux calibration using standard IRAF software, distributed by the US National Optical Astronomy Observatory (NOAO). Flux calibration was performed using a spectrum of the standard star Hz2, obtained on a different night but using the same instrumental set-up. Wavelength calibration was done using spectra from Hg and Cd arc lamps, and the residuals indicate that this should be accurate to a few tenths of a nanometre except at the edges of the blue frames.

3 RESULTS

Flux-calibrated spectra for all four candidates (A and B images in each case) are given in Fig. 2. In each case, we identify two objects along the slit in each spectrum, and can clearly distinguish the two spectra. In all four systems, we identify the primary (A) object as a quasar, with a redshift that agrees with the SDSS redshift. In two cases (J033248.5−002155 and J091750.5+290137), we clearly identify the secondary as an M dwarf, most likely with a spectral type around type M5 (e.g. Bochanski et al. 2007). In the case of J034025.5−000820, the identification of the object is less clear; it is hardly visible in the blue, but the spectrum rises steeply to the red. There is a possible identification of a break in the spectrum

[1] SDSS J080623.7+200632 (Inada et al. 2006b), SDSS J083217.0+040405 (Oguri et al. 2008a), SDSS J091127.6+055054 = RXJ 0911+0551 (Bade et al. 1997), SDSS J092455.8+021925 (Inada et al. 2003b), SDSS J122608.0−000602 (Inada et al., in preparation), SDSS J132236.4+105239 (Oguri et al. 2008a), SDSS J135306.2+113805 (Inada et al. 2006b).

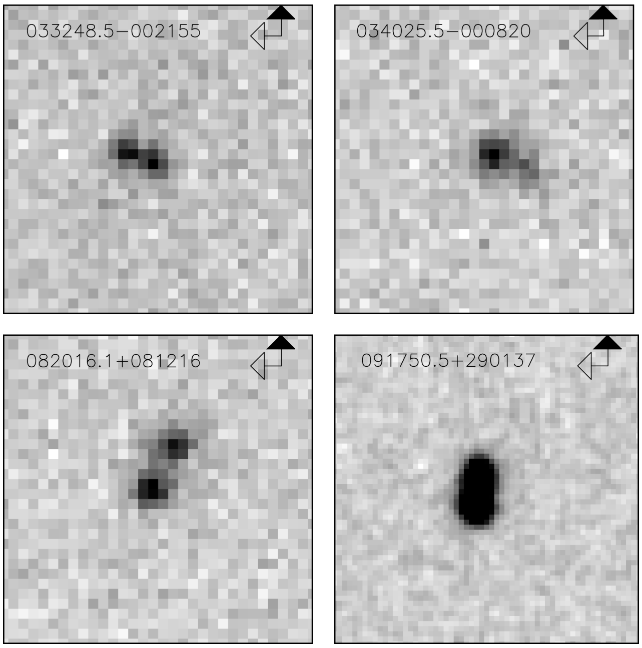

Figure 1. UKIDSS images of the objects observed. Images are in the *H* band except for J091750.5+290137, which is in the *J* band. All images have north at the top and east on the left, and each image is 12.8 arcsec on a side.

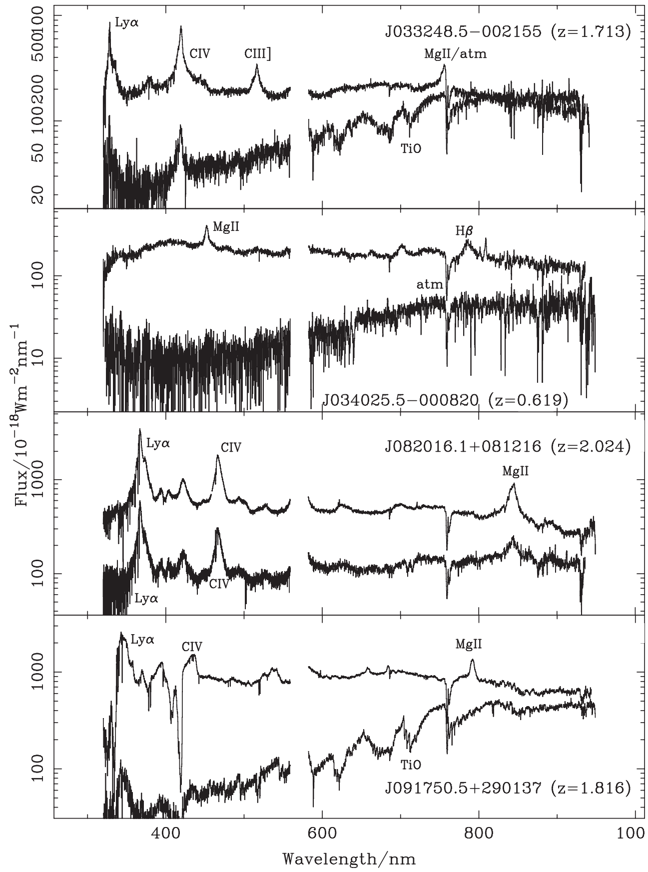

Figure 2. Spectra of the four observed objects. Each panel shows the primary object (a quasar in each case) together with the secondary. The secondary is an M dwarf for two objects (J033248.5−002155 and J091750.5+290137) and a quasar in one case (J082016.1+081216). The SDSS redshifts are given in parentheses. Cosmic rays have been interactively removed from the spectra, and the area affected by the dichroic cut has been blanked. Atmospheric telluric absorption features are visible in the spectra at 760 and 690 nm.

at around 640 nm, which if identified with a galactic 400-nm break feature would imply that it is a galaxy at roughly the same redshift as the quasar. In any case there is no sign of any emission lines which might lead us to conclude that we are dealing with a gravitational lens system.

In the case of J082016.1+081216 (Fig. 3), we clearly see two objects with emission lines; Lyα, C IV and Mg II are identifiable in each spectrum, and C III] is hidden by the dichroic cut. Moreover, if we subtract a scaled version of the primary component, divided by a factor of 6, from the secondary component, we obtain a residual which is redder than either spectrum individually. This is what would be expected from a two-image gravitational lens system, as the lensing galaxy (G) would be expected to lie very close to the fainter image (B) of the lens system, with the brighter (A) image some distance away. The identical spectra, together with the identification of a galactic residual in the fainter component, is convincing evidence that this is a lens system and not, for example, a binary quasar. Unlike in the case of ULAS J234311.9−005034 (Jackson et al. 2008), there is no evidence of any differences in the spectra which might suggest differential reddening of the images within the lensing galaxy. Like ULAS J234311.9−005034, ULAS J082016.1+081216 is a radio-quiet quasar, having no radio identification at the level of 1 mJy in the Faint Images of the Radio Sky at Twenty-cm (FIRST) radio survey (Becker, White & Helfand 1995).

A final indication of lensing (Fig. 4) can be derived from fitting two images to the SDSS and UKIDSS data for J082016.1+081216. A clear trend for reduced separation is seen between the optical and near-infrared; this is exactly as would be expected if a relatively red lensing galaxy is lying between two blue quasar images, and close to the fainter quasar image. The implication of Fig. 4 is that the separation of the two quasar images is approximately 2.3 arcsec, and that the lensing galaxy, which is likely to dominate the flux in the near-infrared, lies approximately 1.8 arcsec from the brighter component. However, it cannot be detected directly from the UKIDSS images alone. We can test this by fitting two PSFs to the *J*-band UKIDSS image (which has the smallest pixel scale, 0.2 arcsec) separated by a fixed 2.27 arcsec separation implied by the blue optical images, and allowing a third Sersic component to be located in between them. A good fit is obtained using the GALFIT software (Peng et al. 2002), but is statistically indistinguishable from the two-component fit, and the residuals for the two fits look very similar and noise like.

A redshift for the galaxy can be derived if we identify the absorption lines seen in the difference spectrum around 710 nm with the Ca H&K doublet at 393.3 and 396.7 nm. Fitting to these lines yields a galaxy redshift of 0.803 ± 0.001 for each line, which, together with an Einstein radius of 1.15 arcsec and an assumption of an isothermal model, predicts a galaxy of velocity dispersion $\sigma \simeq 290\,\mathrm{km\,s^{-1}}$. From the Faber–Jackson relation (Faber & Jackson 1976) as calibrated by Rusin et al. (2003) and using the image separation together with $z_l = 0.803$, we obtain an expected magnitude of $R \simeq 21.4$ for a typical lensing galaxy. The magnitude of the galaxy implied by Fig. 3 is about 0.07 times the total magnitude of the object, or $r \simeq 21.9$, which corresponds approximately to $R = 21.6$. The good agreement with the observed R is further, though circumstantial, evidence for this object being a lens system.

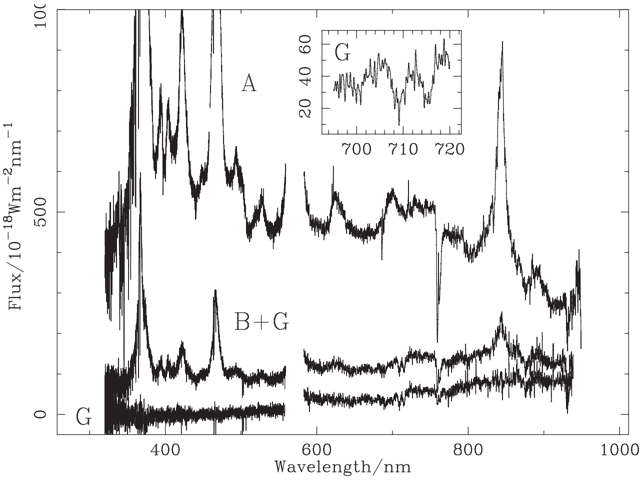

Figure 3. Spectra of the J082016.1+081216 system. The figure shows the primary component (interpreted as the brighter 'A' image of the lens system) and the secondary component (consisting of the 'B' image and the lensing galaxy G) together with the residual (G) from the subtraction of one-sixth of the primary component from the spectrum of the secondary. The residual is redder than either image. It contains a possible set of absorption lines at about 710 nm (inset) which can be identified with Ca H&K at a wavelength of 393.3 and 396.7 nm in the rest frame. Atmospheric telluric absorption features are visible in the spectra at 760 and 690 nm.

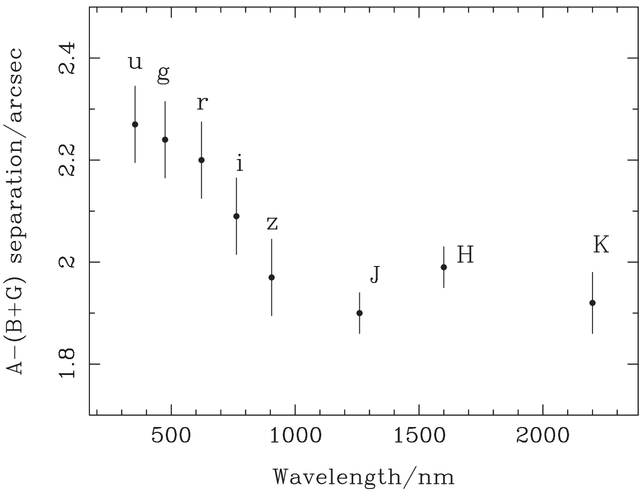

Figure 4. Separation of the primary (A) and secondary (B+G) components in the filters *ugrizJHK* from SDSS and UKIDSS, against wavelength.

If we assume an isothermal model for the galaxy, together with the observed image flux ratio and separation, we obtain a likely time delay of approximately 350 d, assuming $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, between variations of the A and B images. The relatively long delay results from a combination of a high flux ratio and large separation.

4 DISCUSSION AND CONCLUSIONS

We show that the use of the image quality together with the depth of UKIDSS is likely to lead to discovery of lenses in a wider region of parameter space than lenses selected using SDSS alone. This is because the better image quality of UKIDSS should allow the discovery of both smaller-separation lenses and lenses of higher flux ratio. To illustrate this, Fig. 5 shows the image separations and flux ratios of lenses from the SQLS sample. For four-image lenses, the brightness is dominated by an almost unresolved pair of merging images, with a third fainter image and a fourth, typically much fainter image. In this case we take the flux ratio as the brightness of the third image divided by that of the merging pair. Fig. 5 also shows the image separation and flux ratio distribution of lenses from the CLASS survey (Browne et al. 2003; Myers et al. 2003), which has a resolution limit of 0.3 arcsec and a flux ratio limit of 10:1, and of the two MUSCLES lenses found so far. The lens presented here, ULAS J082016.1+081216, has a flux ratio of 6, higher than the limit of the SQLS main survey. In fact, of the SQLS optical lenses with separation $\theta < 4$ arcsec, this lens has the highest flux ratio. Its nearest rival was found by a special imaging programme based on SDSS, rather than SDSS directly (Morgan, Snyder & Reens 2003).

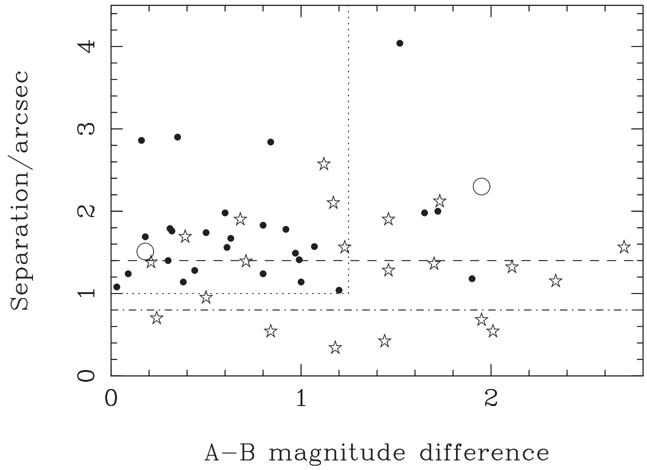

Figure 5. Image separations and flux ratios from the SQLS lens sample (Inada et al. 2003a,b, 2005, 2006a,b, 2007, 2009; Johnston et al. 2003; Morgan et al. 2003; Oguri et al. 2004a,b, 2005, 2008a,b; Pindor et al. 2004; Pindor et al. 2006; Kayo et al. 2007; Morokuma et al. 2007; Ofek et al. 2007). The two MUSCLES lenses (Jackson et al. 2008 and this work) are indicated as open circles. The UKIDSS median image quality (dot–dashed line) and SDSS (dashed line) are indicated, together with the dynamic range and lens separation limit of the SDSS statistical sample (dotted line). The primary contribution of this survey is likely to be lenses at higher flux ratio and smaller separation. CLASS survey lenses, with a separation limit of 0.3 arcsec and flux ratio limit of about 10 (2.5 mag) are indicated by stars. One CLASS lens is just outside the plot, with a separation of 4.6 arcsec and flux ratio 0.86 mag.

We can extrapolate from the existing SQLS and CLASS surveys to attempt to estimate the lens yield of MUSCLES after all follow-up has been done. Only eight of the 22 CLASS lenses lie in the part of the separation/flux-ratio diagram accessible to the main SQLS survey. Assuming that MUSCLES can detect lenses of up to 10:1 flux ratio, and with separations >0.6 arcsec (cf. the SQLS survey limit of 1 arcsec for average seeing of 1.4 arcsec in SDSS), this implies a potential yield of over 50 new lenses compared to the 30 in SQLS. The actual number may be somewhat less than this, as lenses with high flux ratios *and* lower separation will be harder to detect. There will also be a reduction because the currently planned footprint of UKIDSS is around 4000 deg^2, compared to around 9000° in the SDSS spectroscopic area. It is to be hoped that extensions to UKIDSS in the future may remedy this, however. Moreover, many of the UKIDSS detections of the SDSS quasars are at a level where high flux-ratio secondaries may be harder to find. Nevertheless, a well-selected lens sample approximately two times greater than the existing SQLS sample has implications for studies of galaxy evolution. For example, the limits of Matsumoto

& Futamase (2008), based on the SQLS sample alone together with the lens–redshift test, do not currently allow us to rule out the hypothesis of no evolution in lens galaxy number density or velocity dispersion. We expect that an increase in the statistical lens sample should allow this to be done.

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